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Increasing Transmission Grid Flexibility by TSO Coordination to Integrate More Wind Energy Sources While Maintaining System Security

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***Abstract*—The transmission grid in Europe is interconnected to guarantee the security of supply and to facilitate the competition among different market players, thereby making the system highly meshed. It is a challenging task for the transmission system operators (TSOs) to manage the power flows in their system, especially in the light of integration of renewable energy generation sources into the transmission system. The intermittent nature of such generation sources creates variable power flows and loop flows, in turn, questing for installation of controllable devices to manage these flows. The TSOs are currently installing such devices to cope with the situation. A proper coordination is needed for the operation of these devices, since they can lead to adverse effects on power flows in a meshed system. Coordination among TSOs in Central Western Europe (CWE) is performed, however, not towards a full system-wide objective, since there is no regulatory framework that exists for such coordination. This paper focuses on the potential of coordination among TSOs with respect to operation of the controllable devices. Two aspects are investigated: management of constraints in the system in the day-ahead scheduling process and wind in-feed optimization. Both approaches are implemented at the Regional Security Center and tested on a high-stress situation in the CWE region. Furthermore, a case study at the coordination center is performed using actual data for the month of January 2013 to assess the usefulness on a longer time period.**

***Index Terms*—Coordination, high-voltage direct current (HVDC), phase-shifting transformer (PST), transmission system operations, uncertainty management.**

NOMENCLATURE

l	Line index.
t	Time index.
b	Node index.
N_h	Number of hours.
c	Contingency index.
j	PST index.
N_{PST}	Number of PSTs.
N_b	Number of nodes.
$F_{l,c,t}$	Flow through line l for contingency c at hour t.
$\phi_{j,t}$	Angle of PST j at hour t.
$K_{l,c,t,j}$	PSDF of line l for contingency c at hour t corresponding to PST j.
$D_{l,c,t,b}$	PTDF of line l for contingency c at hour t corresponding to node b.
G_b	GSK for node b.

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I. INTRODUCTION

TRANSMISSION system operators (TSOs) in Europe are experiencing challenges in both planning and operations of their power system. Different factors force TSOs to use a completely different approach compared to the situation before unbundling [1], [2]. A strong increase in variable renewable energy, mainly wind and solar, increased market operations, thereby creating additional and variable flows and higher uncertainty in energy flows due to variable injections, distant balancing actions, and cross-border trading are some of the factors to be mentioned among many others. As a result, the power system is operated closer to its limits, while under higher uncertainty. Increasing control actions are needed, including expensive generation dispatch and renewables curtailment.

Power flow controlling devices (PFCs), such as phase-shifting transformers (PSTs) and high-voltage direct current (HVDC), have gained increasing attention and application in the power system. Several PFCs are installed in the European power system.

1) They give more control options to the TSOs after unbundling of power systems.
2) They help to manage variable energy flows caused by increased cross-border trade and higher intermittent generation.
3) Reliability of supply demanded the need for interconnections to different regions and also to different synchronous zones, thereby requiring TSOs to invest in HVDC connections.
4) Through control, they can offer firm capacity to the market.

These devices offer a solution which increases transmission capacity while avoiding the construction of new energy corridors, or by using underground direct current (dc) cables. PFCs allow the system to be operated upto its limits. A significant number of PFCs, such as PSTs, are installed among different

TSOs. Before creating coordination centers, their operation used to be mostly done on a TSO basis and not on a system-wide basis. However, negative consequences of PFC actions may exist on neighboring zones as well as negative interactions among PFCs, even during steady state operations.

The effect of PFCs on grid operation is well understood. A Belgian case study is described in [1] for different stages of grid management: investment, planning, and scheduling and operations using power flow controlling devices, including practical aspects. The case study comprises two technologies: PST and HVDC. In [2], a methodology to include PSTs in the 24 hours day-ahead scheduling process of the TSOs is presented. In [3], the necessity of coordination of PFCs in a meshed transmission system is shown. An approach of a coordinated control of multiple PSTs is developed in [4] to decrease unscheduled flow experienced by a TSO inside an interconnection. The authors in [5] studied how PSTs can be controlled in order to obtain an optimal or near-optimal situation to maximize the total transfer capacity between zones as an indicator for the degree of coordination of PSTs. Analytic expressions are derived in [6] to gain insight in the operating principles of PSTs in a highly meshed grid. An optimal power flow (OPF) model is proposed in [7] that takes the uncertainties of both load and renewable energy into account. Reference [8] presents an integrated OPF with phase shifter approach to enhance power system security. A genetic algorithm-based procedure is designed in [9] for the topological optimization of a network against parallel flows. In [10], a methodology for the PST optimization in the security constrained scheduling applications is presented. Reference [11] presented a practical model of PST to solve the problems of overloads in contingency analysis and minimizing line losses in transmission systems. A novel approach has been proposed in [12] to identify the deviations of power flows which are controlled by multiple PSTs.

The authors in [13] proposed an analysis of dealing with uncertainty for security management by TSOs in the context of day-ahead planning and intraday operation. They proposed an abstract formalization of this task in the form of a three-stage decision-making problem under uncertainties in the min-max framework, where the three stages of decision-making correspond, respectively, to operation planning, preventive control in operation, and postcontingency emergency control.

To the best of our knowledge, no works are done using nodal and angular sensitivities in numerical algorithms for coordination of PSTs to better manage the system in its daily operations and handle wind uncertainty forecasts, demonstrated on a real system.

This paper shows that an increase in coordination among TSOs with respect to PST operation indeed helps to manage the system in a significantly better way. Suitable methodologies have been developed to include PST coordination in scheduling process of the TSOs in order to handle critical contingencies in the system. The developed methodologies are helpful in daily operations of the power system. This paper also shows that an increase in PST coordination aids in integrating more renewable energy into the system. This methodology is helpful in planning of the system for the next day. In this aspect, a tool has been developed for CORESO, a Regional Coordination Service Center in Central Western Europe (CWE), which supplies daily grid security forecasts and proposes remedial actions when necessary to the control centers of the participating TSOs (which are Belgian TSO-Elia, French TSO-RTE, British TSO-National Grid, East German TSO-50Hertz, and Italian TSO-Terna) to include PST scheduling in their operational processes for all time scales (D-2, D-1, and intra-day), both for system operations and planning. The developed methodologies, in the form of a prototype, have been rigorously tested for the whole month of January 2013 with real system data and showed promising results in terms of better system management and handling uncertainties in the system.

However, the developed algorithms are not limited to applications using PSTs and HVDC but can be applied to other flexible alternating current transmission system (FACTS) devices [14], including TCSC, SSSC, UPFC, and Sen transformers [15].

The paper is organized as follows. The TSOs that belong to the CWE region are described in Section II. Section III describes power system operations in different time frames. The proposed methodologies for PST coordination to manage the system constraints of CWE and handle wind uncertainties are presented in Sections IV and V, respectively. The use of the methodologies is tested on the CWE region for the month of January 2013. A short summary of that case study is presented in Section VI. The conclusion in Section VII summarizes the main features of the approach.

II. Current Placement of PSTs in CWE

The CWE region has a key role in the European transmission grid, i.e., the ENTSO-E grid. The TSOs that belong to the CWE region are Amprion GmbH, Creos Luxembourg S.A., Elia System Operator S.A., EnBW Transportnetze AG, RTE EDF Transport, Tennet TSO B.V. (The Netherlands), and Tennet TSO GmbH (Germany). Eight PSTs in this CWE region are considered in this work, the detailed placements of which can be found in [2].

III. Power System Operations in Different Time Frames

Power system operation is a term which encompasses an entire range of activities performed by the different stakeholders. The activities of the operation fall within a time frame of several weeks, days or, hours in advance, up to real time. This is shown schematically in Fig. 1.

Months to days in advance, the operational planning of the power system focuses on maintenance, long-term generation scheduling, and assessing the grid capacity between zones. Closer to actual operations (D-2), the guaranteed available system capacity between zones is determined and given to the market. Based on this input, market participants make offers to the market. The bids for the actual day come in the day before the actual operation (D-1), before gate closure. The different system operators perform the day-ahead congestion forecast (DACF) to determine whether the provided generation schedule can be maintained or whether there are

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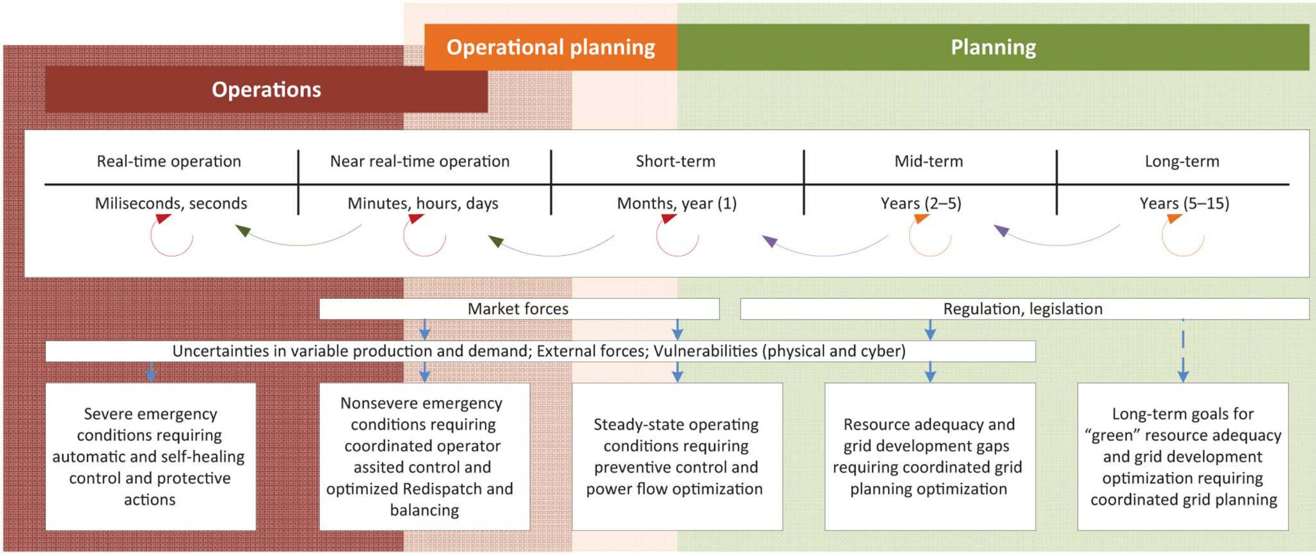

Fig. 1. Smart operation and planning time frames [16].

adjustments needed. The DACF forecasts the system flows for each individual hour, while taking "N-1" constraints into account. The DACF also includes the expected generation from renewable energy sources. These adjustments can be through market actions, or through TSO preventive actions such as the control of PFCs. The DACF forms the basis for the security assessment done by the TSO. During the day itself, the TSO monitors the grid behavior, which in normal operation always differs from the predicted state due to contingencies in the system, unforeseen generation shifts (possibly due to weather conditions), changes in demand, etc. Furthermore, the system continuously changes its operating state because of the numerous variables in the system. If the predictions are close enough to the actual operation point, the TSO performs its planned operation. Generators (and other market participants) may also trade electricity in intraday, resulting in possible changes from the foreseen schedules. Regular energy trade and balancing actions occur throughout the day. Larger shifts from the predicted operating point may occur as well. This can happen through large deviations in generation or load (due to an outage or unforeseen shifts in generation) or through outages in the grid. Such larger shifts can cause the system to move beyond the secure operating boundaries of the system. At such occasion, the system operator takes action through additional preventive actions or even corrective actions.

This paper focuses on the time frame between the capacity allocation and the preventive scheduling of the power system in the day-ahead operations. Similar approaches can also be used in the capacity allocation and during intraday or real-time operations.

The following two sections explain the developed methodologies and show the simulation results of PST coordination in CWE to handle contingencies (Section IV) and to increase renewable energy penetration (Section V) in the system. In other words, uncertainty handling with the help of PST coordination is shown. The input data for all of the simulations are the real CWE grid data coming from European-wide DACF process. DACF files contain the data of the CWE grid (line impedances, admittances of capacitor banks, etc.) and its situation (line outages, circuit breaker status, taps of PSTs, etc.) for the next day. Starting from this grid data, a full ac power flow is performed with the network analysis tool of CORESO, called Convergence. The main output of Convergence is the base case or reference flows, but Convergence is also able to compute nodal sensitivities [Power Transfer Distribution Factors (PTDFs)] relative to nodal injections and angular sensitivities [Phase Shifter Distribution Factors (PSDFs)] relative to the angle of PSTs. A selection of the most important lines from a reliability perspective, named Critical Branches (CBs), around the area of interest is made. Then they are crossed to a selection of most impacting outages. Forty-five CBs in CWE are considered for experimentation. The effect of outage of each CB on the other 44 CBs is then considered for generating the "N-1" cases. The list of CBs and outages is made by the CORESO operators based on their expertise. For these lines and outages, reference flows and sensitivities are used to construct a linear approximation of the flows on the lines when modifying angle of PSTs and nodal injections.

IV. Constraint Management

A. *CM With System Margin Optimization* $(\mathrm{CM}_{\mathrm{MO}})$

A first approach to manage "N" and "N-1" constraints attempts to gain an overall margin of the transmission system of CWE with the help of installed PSTs, in turn, creating room to handle more uncertainties in the system. An optimization problem $\mathrm{CM}_{\mathrm{MO}}$ has been formulated, the objective of which is to reduce the loading of the maximum loaded line in the system, thereby diverting power flows to less loaded lines and gaining system margin, if possible, by the PSTs. The optimization is formulated using a linear approximation of flows in order to keep the whole formulation linear.

1) Problem Formulation: The formulation of the optimization problem is as follows:

$$\min \quad \psi_t \qquad \forall t \quad (1)$$

s.t.:

$$F_{l,c,t} = F^{\text{ref}}_{l,c,t} + \sum_{j=1}^{N_{\text{PST}}} [K_{l,c,t,j} \times (\phi_{j,t} - \phi^{\text{init}}_{j,t})] \quad \forall l,c,t \quad (2)$$

$$-F^{\max}_{l,c,t} \times \psi_t \leq F_{l,c,t} \leq F^{\max}_{l,c,t} \times \psi_t \quad \forall l,c,t \quad (3)$$

$$\phi^{\min}_{j,t} \leq \phi_{j,t} \leq \phi^{\max}_{j,t} \quad \forall j,t \quad (4)$$

$$\psi_t \geq 0 \quad \forall t. \quad (5)$$

Equation (1) represents the objective function which minimizes the loading of the highest loaded line in the system. Constraint (2) represents the linear approximation of line flows in each line l for each contingency c during hour t in terms of PSDF sensitivities for each PST j. $F^{\text{ref}}_{l,c,t}$ is the initial flow through line l for contingency c at hour t, based on the bus injection vector. Constraint (3) represents the upper and lower bounds on the line flows, multiplied by ψ which is a positive variable according to constraint (5), to identify the maximum loaded line in the system. Finally, constraint (4) represents the upper and lower bounds for each PST angle. $\phi^{\text{init}}_{j,t}$ is the angle of PST j corresponding to the tap position present in DACF file for hour t.

2) Testing the Methodology: The highly stressed CWE grid of June 25, 2012 is used to test the approach $\mathrm{CM_{MO}}$. A high amount of wind generation in Germany was foreseen for this day, leading to high exports from Germany to the neighboring grids. Moreover, three 400 kV lines, Doel-Avelgem, Bruegel-Mercator35, and Bruegel-Mercator36, owned by Elia were out of service thereby making the CWE grid weaker. The most important constraints at CWE for that day are shown in Table I. It is important to note that the DACF files already contain PST set points, which are based on each TSOs-expected operation but are neither coordinated nor optimized. CORESO proposed to cancel some outages in Germany and proposed preventive tap settings for different PSTs of this area in day-ahead.

A margin analysis graph is drawn to show the effectiveness of the formulated optimization problem. In this graph, the per unit line flows of the CB lines are sorted from highest to lowest both for "N" and "N-1" situations and for all 24 h, before and after optimization. The "initial" and "optimized" curves present the per unit values of the initially scheduled flows and the optimized flows for each line and for each contingency. Fig. 2 shows such a margin analysis graph for this case. The figure shows the results for all 24 h and the number of data points along the horizontal axis is 48 600 [(45 CBs for basecase + 45 "N-1" cases × 44 CBs) × 24]. Fig. 3 shows the zoomed-in part of the graph that is most relevant.

From Fig. 3, it is evident that the system is initially overloaded (during a contingency) with an overloading percentage of 141% represented by the solid line, which is also evident from Table I. The dashed line in the figure shows the system loading by optimizing the Belgian PSTs (Zandvliet and 2 Van Eycks) only. It is clearly seen that although there is an improvement, the Belgian PSTs alone are unable to even make the system secure let alone gaining system margin.

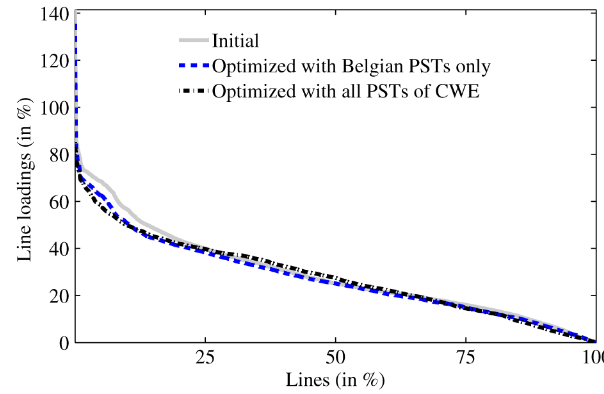

Fig. 2. Margin analysis graph for $\mathrm{CM_{MO}}$.

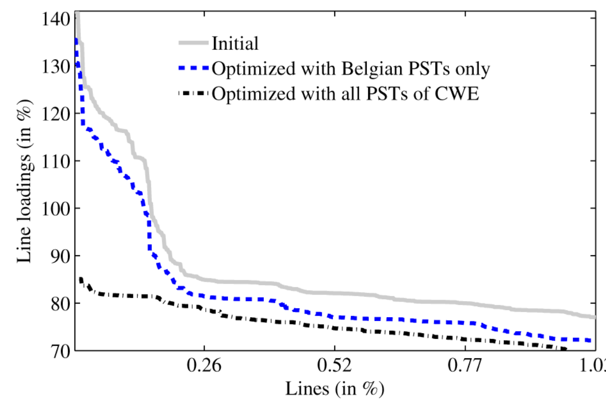

Fig. 3. Zoomed view of the margin analysis graph for $\mathrm{CM_{MO}}$.

The dashed–dotted line represents the system loading with all eight PSTs in CWE taking part in the optimization. The methodology allows to reduce the maximum flow to 85% making the system secure. An additional 15% of system margin is gained by the PSTs. The example shows the validity of the methodology, and the benefit of (international) coordination of PSTs to manage congestion in a meshed grid such as CWE.

The upper part of Fig. 4 shows the tap positions of the PSTs after optimization, taking all the PSTs into account. It is clear that the optimization problem proposes tap changes every hour to optimize system margin both for "N" and "N-1" cases. It may also propose a significant amount of tap changes from their corresponding DACF values and may even reach the extreme tap positions of the PSTs, such as the PSTs in Diele in this case.

Current operation of CWE grid limits the practical interest of this algorithm. Moreover, the operators of TSOs are reluctant to change PST taps when the system is already secure. Hence, the algorithm is modified to cater the needs of the operators and to make the system secure with the coordination of PST operation in CWE.

B. CM With Limit Checking ($\mathrm{CM_{LC}}$)

The extension of the algorithm caters to the need of the operators which is to check whether the PST taps present in the DACF files are feasible to manage all "N" and "N-1" constraints in the system. If not, it provides the minimal tap changes from these PST taps present in DACF required to

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TABLE I
FORESEEN CONSTRAINTS IN DACF FOR JUNE 25, 2012

TSO	Contingency				Constraint				
	U (kV)	Substation 1	Substation 2	Code	Overload (%)	U (kV)	Substation 1	Substation 2	Code
Elia	380	Mercator	Busbar	2B	133	380	Doel	Mercator	54
Tennet NL/Tennet DE	380	Meeden	Diele	Axis	141	380	Meeden	Diele	Remaining
Tennet DE	380	Conneforde	Diele	Axis	141	380	Diele	PST	Remaining

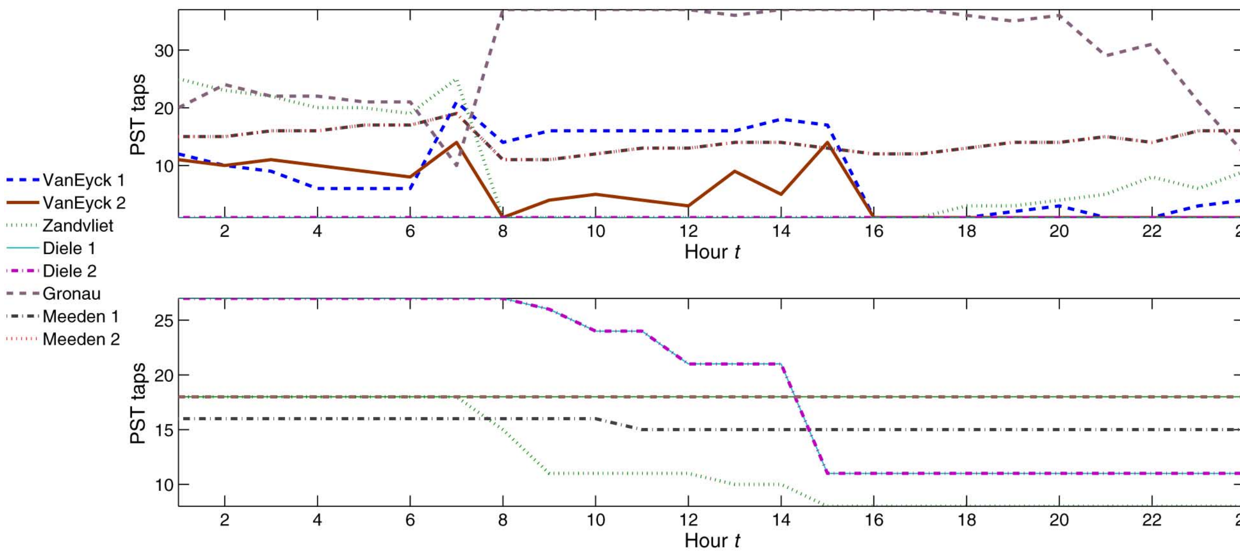

Fig. 4. PST taps (upper: $\mathrm{CM}_{\mathrm{MO}}$; lower: $\mathrm{CM}_{\mathrm{LC}}$).

eliminate the constraints. It is to be mentioned here that no optimization for gaining system margin is taken into account. The tap positions of the PSTs follow that of the previous hour until and unless any constraint is violated. If violated, the PSTs are switched to their corresponding taps determined by the algorithm to evade the constraint. This is practical from the system operation point of view.

1) Problem Formulation: The formulated optimization problem is as follows:

$$\min_{\phi} \quad \sum_{t=1}^{N_h-1}\sum_{j=1}^{N_{\text{PST}}}\gamma_{j,t} + W_1 \times \sum_{j=1}^{N_{\text{PST}}}\chi_{j,1} + W_2 \times \sum_{t=2}^{N_h}\sum_{j=1}^{N_{\text{PST}}}\chi_{j,t} \qquad \forall j,t \qquad (6)$$

s.t.:

$$-\gamma_{j,t} \le (\phi_{j,t} - \phi_{j,t+1}) \le \gamma_{j,t} \qquad \forall j,t \qquad (7)$$

$$-\chi_{j,t} \le (\phi_{j,t} - \phi_{j,t}^{\text{init}}) \le \chi_{j,t} \qquad \forall j,t \qquad (8)$$

$$F_{l,c,t} = F_{l,c,t}^{\text{ref}} + \sum_{j=1}^{N_{\text{PST}}}[K_{l,c,t,j} \times (\phi_{j,t} - \phi_{j,t}^{\text{init}})] \quad \forall l,c,t \qquad (9)$$

$$-F_{l,c,t}^{\max} \le F_{l,c,t} \le F_{l,c,t}^{\max} \qquad \forall l,c,t \qquad (10)$$

$$\phi_{j,t}^{\min} \le \phi_{j,t} \le \phi_{j,t}^{\max} \qquad \forall j,t \qquad (11)$$

$$\gamma_{j,t} \ge 0 \qquad \forall j,t \qquad (12)$$

$$\chi_{j,t} \ge 0 \qquad \forall j,t. \qquad (13)$$

The weight values W_1 and W_2 are taken to be 25 and 0.01, respectively, after performing rigorous tests. Constraints (9) and (11) are same as that of constraints (2) and (4), respectively. Constraint (10) is different from constraint (3) in the sense that no margin optimization is done in this formulation, thereby leading to the absence of term ψ in this constraint.

Constraints (7) and (8) are the essence of this optimization. Constraint (7) makes the change in PST angle of PST j between successive hours to be as minimum as possible by the variable γ, which is minimized in the objective function (6) over all PSTs in the system, represented by its first term. In other words, this constraint takes into account the PST angle change if and only if any "N" or "N-1" constraint is violated in the system, or else follows the angle of the previous hour. Constraint (8) makes the PST angle of PST j to remain as close as possible to its reference value given in the DACF files, which is minimized in (6) over all PSTs, represented by its third term. In other words, this constraint checks whether the PST angles included in the DACF files are feasible or not. The second term in (6) tries to keep the PST angles of all the PSTs for the first hour equal to the values in DACF files and is heavily penalized.

2) Testing the Methodology: The CWE grid data of June 25, 2012 are considered for this case. Fig. 5 shows the margin analysis graph for this case, and Fig. 6 shows the zoomed view of the part of interest.

The solid line in Fig. 6 corresponds again to the initial, non-coordinated case, with a number of lines loaded above 100%. The optimization problem is unable to solve all the system constraints solely with the Belgian PSTs, and the problem turned out to be infeasible. In other words, the optimization problem is unable to find feasible tap positions of the Belgian

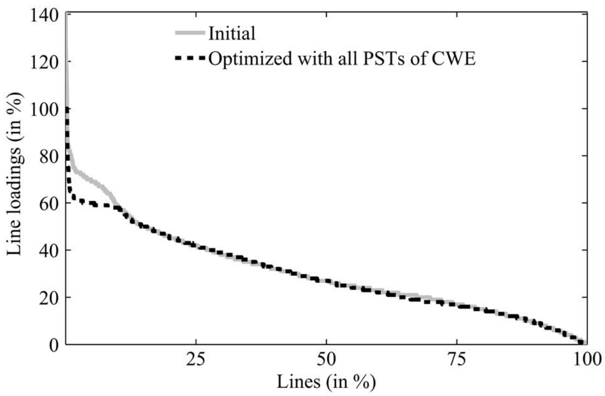

Fig. 5. Margin analysis graph for $\mathrm{CM}_{\mathrm{LC}}$.

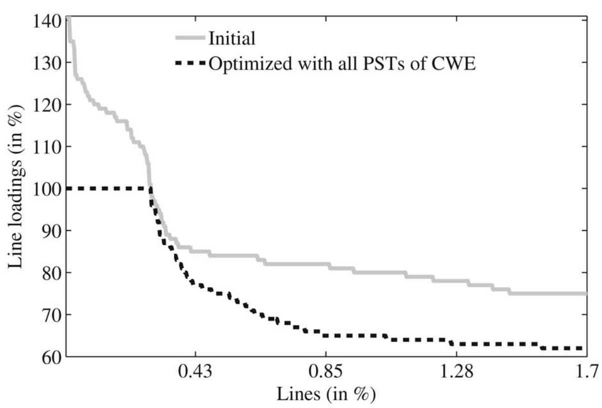

Fig. 6. Zoomed view of the margin analysis graph for $\mathrm{CM}_{\mathrm{LC}}$.

PSTs that can solve all "N" and "N-1" constraints of the system. As it is clear from the $\mathrm{CM}_{\mathrm{LC}}$ analysis, the coordinated action of all the PSTs in CWE indeed is able to secure the system by bringing the system from a negative margin (overload) to a zero margin (represented by the dashed line in the figure), which is the main goal for the extension of the algorithm.

The lower part of Fig. 4 shows the PST tap values that are proposed by the algorithm to evade the constraints. The initial PST tap values present in the DACF files are not able to manage these constraints, and the algorithm proposed the necessary tap changes required to alleviate the constraints and brings the line flows within their maximum limits. This output is closest to the operator behavior and proposes tap changes between successive hours only when "N" and/or "N-1" constraints violations are detected. It is evident from the figure that the "N-1" congestion in Belgium starts at hour 8, and the algorithm proposes a tap change from 18 to 15 for the Zandvliet PST to solve the congestion. When the congestion worsens, the algorithm proposes additional tap changes (from 15 to 11 at hour 9, from 11 to 10 at hour 13, and from 10 to 8 at hour 15) to manage the situation until the congestion is solved. From hour 15, no congestion is detected, and hence, the algorithm proposes no new tap changes and keeps the tap 8 setting till the end of the day.

Similarly, the algorithm also proposed some tap changes on Meeden and Diele PSTs (from 33 to 27 for Diele PSTs and from 17 to 16 for Meeden PSTs at hour 1) when the congestion starts at this part of the grid. Moreover, when the congestion worsens, additional tap changes are proposed (from 27 to 26 at hour 9, from 26 to 24 at hour 10, from 24 to 21 at hour 12 and from 21 to 11 at hour 15 for Diele PSTs and from 16 to 15 at hour 11 for Meeden PSTs).

V. Wind In-Feed Optimization (WO)

The installed wind capacity in CWE has sky-rocketed in the last decade. A significant amount of both onshore and offshore wind farms has been installed in CWE. Currently, approximately 31 GW of wind capacity is installed in Germany and more than 100 GW in Europe. During high-wind periods, a significant amount of electrical power is generated by the wind farms. Sometimes, it becomes impossible to inject this amount of wind power into the system due to congestion in some parts of the CWE grid. Hence, wind curtailment is done in order to operate the grid securely.

PSTs in CWE can have a significant impact on the integration of wind energy into the system. By diverting power flows, the PSTs can relieve congestion in some parts of the grid which lies under their influence, thereby aiding in more integration of wind energy into the system.

1) Problem Formulation: The WO methodology allows to evaluate an upper bound of the amount of wind power increase that may be accepted in the system. The formulation of the optimization problem is as follows:

$$\max \quad \beta_t \qquad \forall t \qquad (14)$$

s.t.:

$$F_{l,c,t} = F^{\mathrm{ref}}_{l,c,t} + \sum_{j=1}^{N_{\mathrm{PST}}} \left[K_{l,c,t,j} \times \left(\phi_{j,t} - \phi^{\mathrm{init}}_{j,t} \right) \right]$$

$$+ \sum_{b=1}^{N_b} [\beta_t \times D_{l,c,t,b} \times G_b] \qquad \forall l,c,t \qquad (15)$$

$$- F^{\max}_{l,c,t} \le F_{l,c,t} \le F^{\max}_{l,c,t} \qquad \forall l,c,t \qquad (16)$$

$$\phi^{\min}_{j,t} \le \phi_{j,t} \le \phi^{\max}_{j,t} \qquad \forall j,t. \qquad (17)$$

Equation (14) represents the objective function which maximizes wind in-feed (an optimization free variable) into the system. Constraint (15) is same as that of constraint (2) except that there is one additional term which represents the additional stress that can be imparted to the system with the help of a certain injection vector called Generation Shift Key (GSK). GSKs are defined as factors by which the generation is increased in some nodes, specifically, at the production park and compensating these increases in other nodes, generally, at the conventional generation nodes. As such, the GSK can be considered as the effect of the increase of a given energy vector, e.g., wind on the system flows. It is to be noted that the sum of positive GSKs equals "1" and the sum of negative GSKs equals "-1." Constraints (16) and (17) remain same as that of constraints (10) and (11), respectively.

The main idea in this formulation is to increase a certain injection vector (a certain GSK, made by the CORESO operators based on their experience) until the system hits its limit(s).

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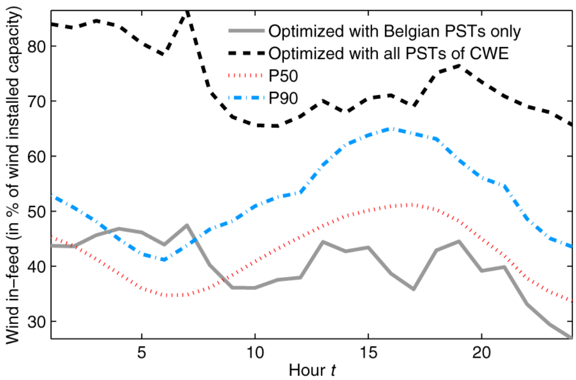

Fig. 7. Wind maximization for June 25, 2012 (WO).

2) Testing the Methodology: The day of June 25, 2012 is again considered for this case. This day is characterized by high-wind forecast values. In reality, wind forecast values are described in terms of P10, P50, and P90 values, in which Pxx represents an "xx" probability that the wind in real time remains below the corresponding value (considering normal distribution).

Fig. 7 shows the results of the formulated problem for this day. The results are expressed in percentage of the installed wind capacity in Germany till 2013, which is 31 GW.

The solid curve in the figure shows the wind in-feed percentage in CWE with the help of Belgian PSTs only, whereas the dashed curve shows the wind in-feed percentage with the help of all PSTs in CWE. It is clearly seen that a significant amount of wind in-feed is possible with the help of coordination among TSOs in CWE with respect to PST operation. In this case, operation of Belgian PSTs alone cannot even handle the forecasted wind values or P50 values from hours 9 to 24, since the solid curve is below the dotted curve (P50) in the figure. Again, coordination of PSTs helped in achieving wind P90 values in this case, since the dashed curve is above the dashed–dotted (P90) curve for all of the hours.

VI. Case Study: CWE Region During the Month of January 2013

The developed methodologies have been rigorously tested on CWE grid data for each day of the whole month of January 2013 using actual hourly system forecast data. Fig. 8 shows the CWE network that has been simulated for the whole month to verify the developed optimization modules. The data consist of the reference flows and the sensitivities with respect to bus injections and PSTs for 24 timestamps for each day of the month. The data for each day were huge, comprising approximately 5 GB.

This study shows the effectiveness of the developed algorithms in Sections IV-A and V. Fig. 9 shows the reduction in loading of the highest loaded CB after optimization with respect to the initial loading of the highest loaded CB before optimization for each hour of the whole month. It is to be mentioned here that the highest loaded CB after optimization can be different from the corresponding one before optimization, since the margin of the system is determined by the distance of the maximum loaded line from its corresponding limit. It is evident from the figure that the system initially was not operated in N-1, leading to overload situations for many cases in the month (initial loading above 100%), and the algorithm is able to relieve the overloading and brings the system to a secure state for all of the cases. A linear trend is seen in the figure which suggests that the reduction of the loading is higher for the lines which are initially very highly loaded. This proves the effectiveness of the formulated optimization problem in Section IV-A to optimize system margin. This algorithm is helpful to manage contingencies and reduces the need for costly measures such as generation redispatch to manage system congestion.

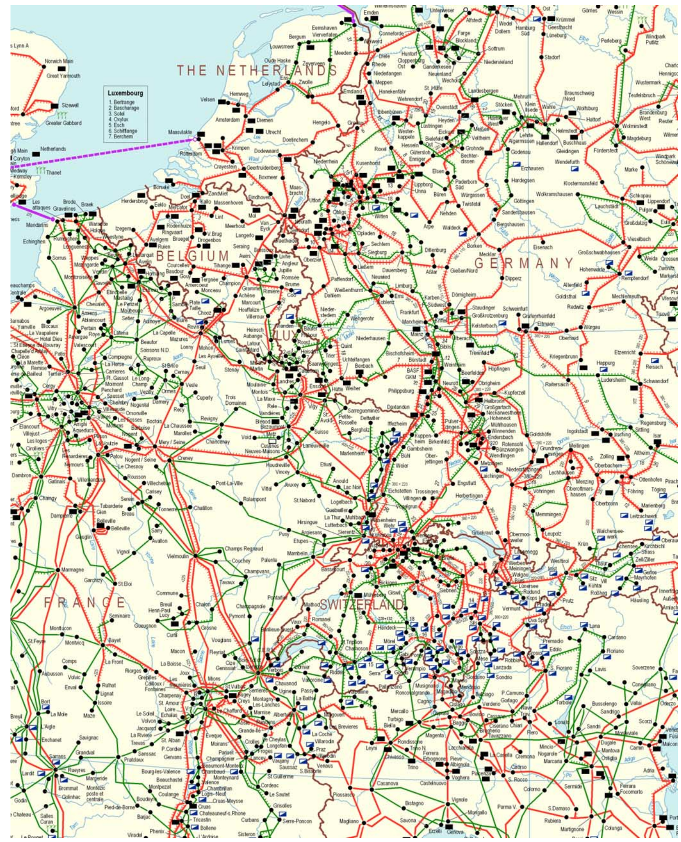

Fig. 8. Transmission system of CWE [17].

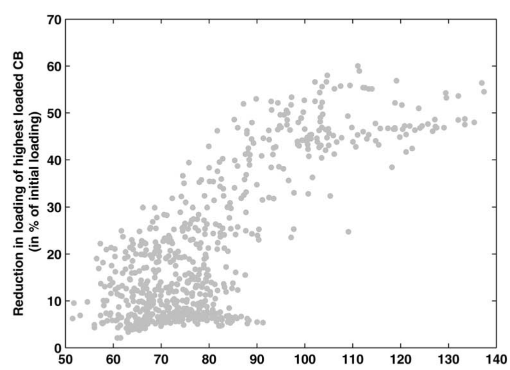

Fig. 9. Reduction of the highest loaded CB for every timestamp of January 2013 with all PSTs optimized $\mathrm{CM}_{\mathrm{MO}}$.

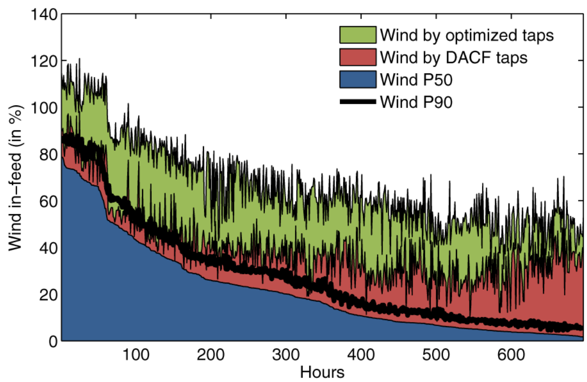

Fig. 10. Wind maximization for January 2013 (WO).

Fig. 10 shows the results of the wind in-feed optimization stated in Section V. The blue area represents the forecasted wind values or P50 values for the whole month. The red area shows the additional stress over and above the wind forecasted values that can be handled with the help of all the PSTs in CWE, the taps of which are fixed to their DACF values. The result is for a given direction of stress, i.e., for a certain GSK. The wind P50 values are already integrated in the DACF files. The green area shows the additional stress that can be handled with all the PSTs optimized. The black line represents the wind P90 values. It is evident from the figure that P90 values of forecasted wind values can be achieved for most of the cases with optimized PST coordination, as the green area is mostly above the black line. Hence, a significant amount of additional wind in-feed is possible in CWE with the help of PST coordination. Hence, an increase in TSO coordination with respect to PST operation indeed helps to achieve a secure system, thereby providing room to maneuver uncertainties in the system.

VII. Conclusion

The actual in-feed from renewable energy sources (RES) into a transmission network can be significantly different than their forecasted values, leading to significant transmission congestion which requires to be alleviated by the TSOs for sake of system security. PFCs can play a vital role in managing congestion which does not incur any significant operational cost to the TSOs.

PFCs installed by TSOs in Europe to alleviate local congestion can be coordinated to achieve better system management and welcome more integration of RES in pan-European transmission network. Algorithms are developed in this paper to minimize congestion in the system during real-time operation, which may arise due to major weather changes that can reduce forecasted capacities. The developed algorithm can help the TSO operators to enhance security margin or alleviate constraints for a power system like CWE. It is shown that the coordination in operation of these devices indeed helps to bring the system into a secure state from an overload situation. This, of course, depends on the injection pattern and system topology.

An algorithm to calculate the amount of additional RES generation over and above its forecasted values is also developed in this paper. The application of this additional stress is determined by GSK vector. It is seen that more wind can be integrated into the system with the help of coordination of these devices.

The developed algorithms have been rigorously tested for the whole month of January 2013 using actual power system data at the premises of the TSO coordination center, CORESO. Two cases have been selected to highlight the use of the algorithm in actual system operations. For this, the algorithms were installed on the servers of the French TSO RTE and interfaced with the operating room of CORESO and managed by actual operators. Although from the study, it is evident that in all of the cases the system congestion was reduced and more RES could be integrated into the system. The average margin for wind deviations was approximately 26% of the installed wind capacity for the month of January 2013. It does not mean that 26% more wind turbines can be installed in CWE, but it does mean that a smarter control of PFCs allows for significantly more wind generation or reduced curtailment.

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